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Ambient Carbon Monoxide Monitor

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AMBIENT CARBON MONOXIDE MONITOR

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16. ABSTRACT

A portable instrument has been designed and two units have been built to monitor the concentration of CO in ambient air. The air flows through a sampling section that is approximately 43 cm long with a 28-pass optical system that produces a total path of 12 meters. Gas-filter correlation methods are employed for the detection and discrimination against other gas species in the air. An H_2O monitor built into the main instrument measures the concentration of H_2O and automatically accounts for a small amount of interference by this gas. Interference by all other atmospheric gases is negligible. The minimum detectable concentration of CO is less than 0.02 ppm. The instrument is powered either by batteries or by a battery pack.

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AMBIENT CO MONITOR

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SECTION I

INTRODUCTION

The concentration of CO in unpolluted air typically varies from 0.1 to 0.3 parts per million (ppm). In areas of high automobile traffic the concentration is frequently several ppm, and in some cases it may exceed 50 ppm. In order to study accurately the rates of accumulation and dissipation of CO in the neighborhood of expressways, it is clear that the instrument being used must have a minimum-detectable concentration of no more than a few tenths of a ppm. If the concentration is to be measured in areas away from heavy traffic where the air is only slightly polluted, the instrument must be portable and have a minimum detectable concentration less than 0.1 ppm.

Several commercially available CO monitors have minimum detectable concentrations from a few tenths of a ppm to 10 ppm. These instruments are not portable and are not sufficiently accurate for detailed studies of the distribution of CO in the ambient air. In 1974, Aeronutronic designed and built an ambient CO monitor for EPA under Contract 68-02-1655. This instrument has much higher performance than previously available instruments and has a minimum detectable concentration well below 0.05 ppm. The instrument can be operated from 115 V ac power lines or from batteries and is portable so that it can be moved easily to any location. This report describes two additional monitors built recently for EPA to monitor CO in ambient air. The recent instruments are similar in many ways to the one built previously. A few minor improvements have been made in order to increase the stability and to decrease the time required to flush a sample from the sample section. Scientific personnel at the EPA have found that the sensitivity of the instruments to H_2O and the dependence of the zero-setting and span calibration on temperature are quite acceptable. Values of CO concentration obtained with these instruments compare very favorably with values obtained for the same samples with other instruments.

Gas-cell correlation methods are employed for the detection and for the discrimination against other gases in the atmosphere. The spectral principles of detection and discrimination have been described previously.[1,2] In ambient

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1. Burch, D. E. and J. D. Pembrook. Instrument to Monitor CH_4, CO and CO_2 in Auto Exhaust. EPA-650/2-73-030, October 1973.

2. Burch, D. E. and D. A. Gryvnak. Infrared Gas Filter Correlation Instrument for In-Situ Measurement of Gaseous Pollutants. EPA-650/2-74-094, December 1974.

air the concentration of H_2O may be as great as 4 or 5% in a humid atmosphere. This amount of H_2O produces enough interference in the measurement of CO that the interference must be accounted for in order to achieve the maximum possible accuracy. An accessory built into the basic CO instrument measures the concentration of H_2O in the air and automatically accounts for the interference by this gas.

SECTION II

SUMMARY

Figure 1 shows two photographs of one of the two instruments described herein. The upper panel includes the assembly that contains the 24 V dc to 115 V ac inverter and the dc-to-dc converter used with the battery pack. The interior of the instrument is shown in the lower panel of the figure; the cover plate for the electronics has been turned back to show the electronic cards for the CO channel and the H_2O channel. The instrument is portable and is powered either by 115 V ac line power or by a 24 V battery pack. Only a few minutes are required to convert from one type of power to the other.

A multiple-pass sample cell provides the required sensitivity while maintaining a relatively small instrument. The base length of the sample cell is approximately 43 cm; it is operated at 28 passes to give a total path length of approximately 12 meters. The minimum response time, less than 5 seconds, is limited by the time required to displace the air in the sample section.

Both the CO and H_2O concentrations can be read from meters on the top panel or with a recorder or voltmeter from output jacks. The peak-to-peak noise of the output when employing a 3-second time constant corresponds to less than 0.02 ppm of CO. This more than meets the design specifications for a minimum detectable concentration of 0.05 ppm of CO. Four different concentration ranges are available to read concentrations from the minimum detectable amount to more than 200 ppm. By making a simple gain adjustment, the H_2O concentrations corresponding to full-scale readings of the meter can vary from less than 1% H_2O to more than 5% H_2O.

The outside dimensions of the main box that contains all of the optical components are approximately 62 cm x 27 cm x 12 cm. Switches and control knobs extend beyond these dimensions on the top and on the front side, which includes the carrying handle and the output jacks. The sample exhaust fan extends a few cm beyond one end. The weight of the main assembly is approximately 40 pounds. Threaded holes near the ends of the front and back sides can be used for rack mounting. A sunshade can also be attached to the main assembly by use of these threaded holes. The instrument can be operated while sitting on the 4 legs on the bottom side or on the back side.

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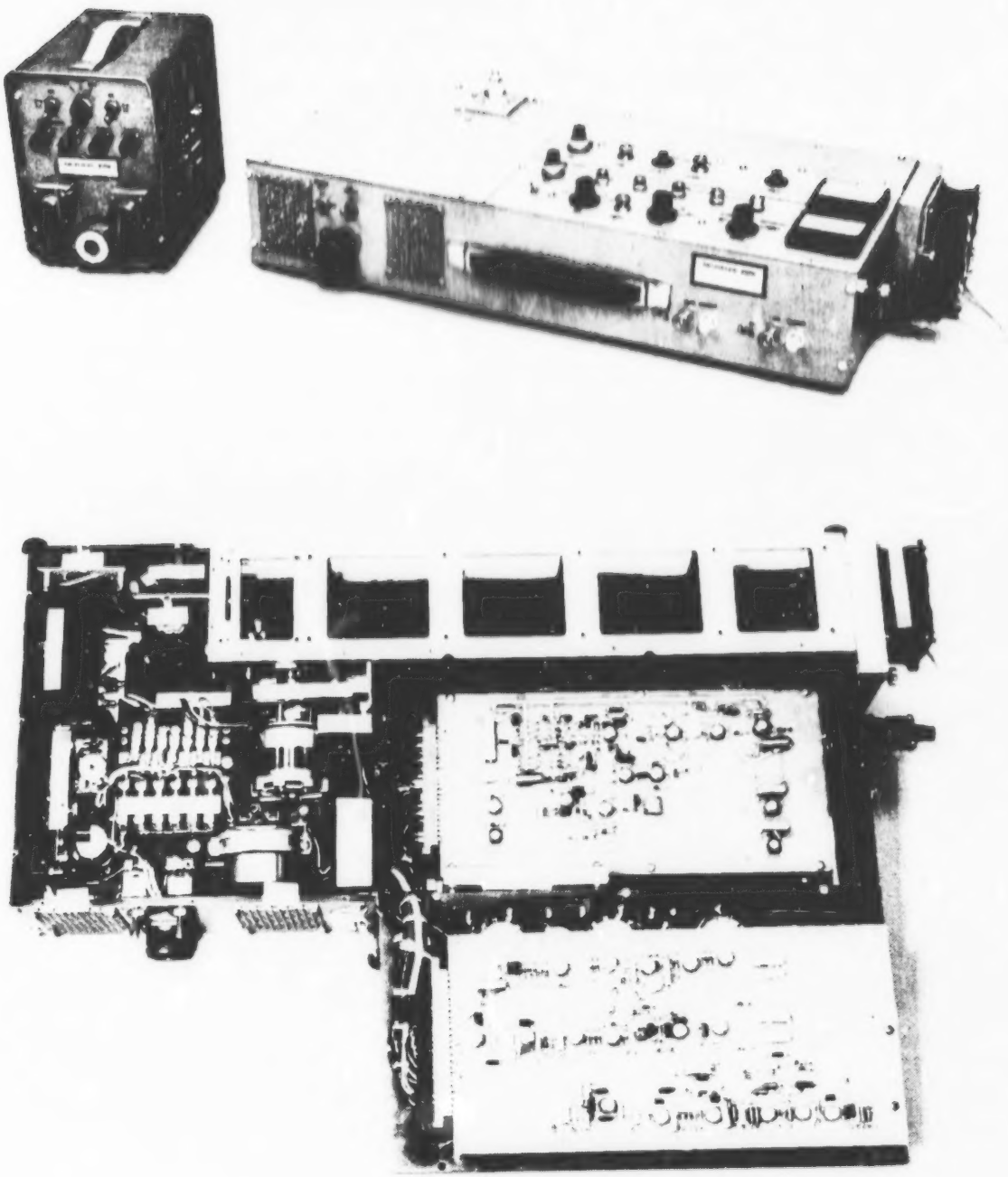

Figure 1. Two photographs of the ambient CO instrument. The upper panel includes the dc-to-ac power supply assembly.

SECTION III

CONCLUSIONS

The results of the tests performed with the two instruments described herein indicate that they are capable of accurately measuring the concentration of CO in ambient air. Interference by H_2O can be accounted for automatically by the use of a simple infrared H_2O monitor that applies a correction signal to the main electronics. The interference by the normal concentration of CO_2 corresponds to an error of less than 0.01 ppm of CO. No significant interference is produced by any gases other than CO_2 and H_2O in the concentrations that are normally found in the atmosphere.

Quite good performance can be achieved when powering the instrument by either 115 V ac line power or by dc power from a battery pack. Approximately 8 hours of continuous dc operation is possible without recharging the pack of 6 small motorcycle batteries. The dc-to-ac inverter that powers the synchronous chopper motor maintains the chopping frequency very nearly constant so that the zero-reading and the sensitivity are quite stable.

SECTION IV

RECOMMENDATIONS

Air samples can be circulated through the sample section by a variety of methods. Two cover plates for the sample section can be removed to allow the ambient air to move freely through the infrared monitoring beam. The recommended alternative to this method is to keep the cover plates in place and draw the air through the sampling section with the exhaust fan provided for that purpose. This latter method has the advantage that it is easy to stop the air flow and flush the sample section with argon to determine the proper zero reading.

It is sometimes desirable to draw outside air through a gas line to the instrument placed inside of a building or a portable laboratory such as a trailer or van. When this procedure is followed the fan or air pump should be placed upstream from the instrument so that the sample section is at or slightly above the local ambient pressure. This prevents the air surrounding the instrument from leaking into the sample section. The adjustable outlet vent should be left slightly open to allow the air to escape without building up a significant pressure in the sample section while avoiding the entrance of the air surrounding the instrument. The air leaving the instrument can be allowed to escape where it leaves the sample section, or it can be carried through pipe or tubing to the outside.

The instruments in their present form provide more sensitivity and accuracy than are required for many applications. Several simplifications could be made to the instrument that would degrade performance, but not enough to prevent its use for many types of monitoring. For example, the thermoelectrically cooled detector could be replaced by an uncooled detector with the same physical dimensions. This change would make it possible to eliminate the power supply for the cooler and would probably decrease the ratio of the signal-to-detector noise by a factor of about 8 to 10. A portion of this loss could be regained by employing a larger radiant energy source and opening up some of the apertures to allow more energy to reach the detector. The small energy source installed in the instrument was chosen to reduce the power requirement, which is particularly important when used in the dc mode with batteries supplying the power. A larger source is recommended if only ac power is to be used. Approximately a factor of 2 in the amount of energy collected could be gained by replacing the aluminum reflective coating on the mirrors of the multiple-pass cell with a dielectric coating with high reflectivity (greater than 99.5%) near 4.6 μm.

Relaxing the accuracy requirements somewhat would also make it possible to eliminate the H_2O monitor and its associated correction circuitry. The

H_2O interference could be partially accounted for by estimating the H_2O concentration or by measuring it by some other means. Uncertainties of less than 0.2 ppm in the measurements of CO concentration could probably be achieved without the detector cooler and the H_2O monitor.

SECTION V

OPTICAL LAYOUT

DESCRIPTION OF COMPONENTS

Figures 2 and 3 illustrate the optical layout of the instrument. The view in Figure 2 is from above the instrument, and the view of the entrance optics components shown in Figure 3 is from the end of the instrument. The source is heated electrically by a wire coiled around a ceramic core; the useful portion is approximately 0.5 cm long and 0.15 cm in diameter. The source is located directly beneath the motor shaft with its long dimension parallel to the shaft. Radiant energy passes through the source window WS to a toroidal mirror M1. After the beam passes through the rotating gas-filter cell, an enlarged image of the source is formed on the entrance window W1 of the sample section.

The rotating gas-filter cell is mounted directly to the shaft of the small 1800 rpm synchronous motor. A transformer provides approximately 60 volts ac for the motor, which dissipates approximately 7 watts. In addition to saving power, which is important when operation in the dc mode, the motor runs more quietly and at a lower temperature at the reduced voltage than it would at full line voltage. Several seconds are required for the motor to reach synchronous speed when it first starts at the reduced voltage; however it easily maintains synchronous speed after it has been attained. The primary coil of the transformer is connected directly to the 115 V ac power line when operating in the ac mode. During dc operation, a dc-to-ac inverter provides the 115 V ac power for the primary of the motor transformer. The frequency of the output of the inverter has been adjusted to 60 Hz so that the motor speed is the same when operating in either the ac or the dc mode.

A shield not shown in either Figure 2 or Figure 3 encloses the rotating gas-filter cell in order to reduce the flow of heat from the source and to prevent dust from accumulating on the windows of the cell. Window WS transmits the energy through the shield.

Much of the good stability and high sensitivity of the instrument is due to the rotating gas-filter cell, which is illustrated in Figure 4. Compartment GC1 is filled with 0.3 atm of pure CO to form the gas filter; compartment GC2 is filled with 0.5 atm of non-absorbing N_2. The 5.1 cm (2 inch) diameter sapphire windows are anti-reflection coated with a single dielectric layer to provide high transmittance near 4.6 μm. Enough CO is introduced in the CO compartment so that its average transmittance, combined with the windows, is

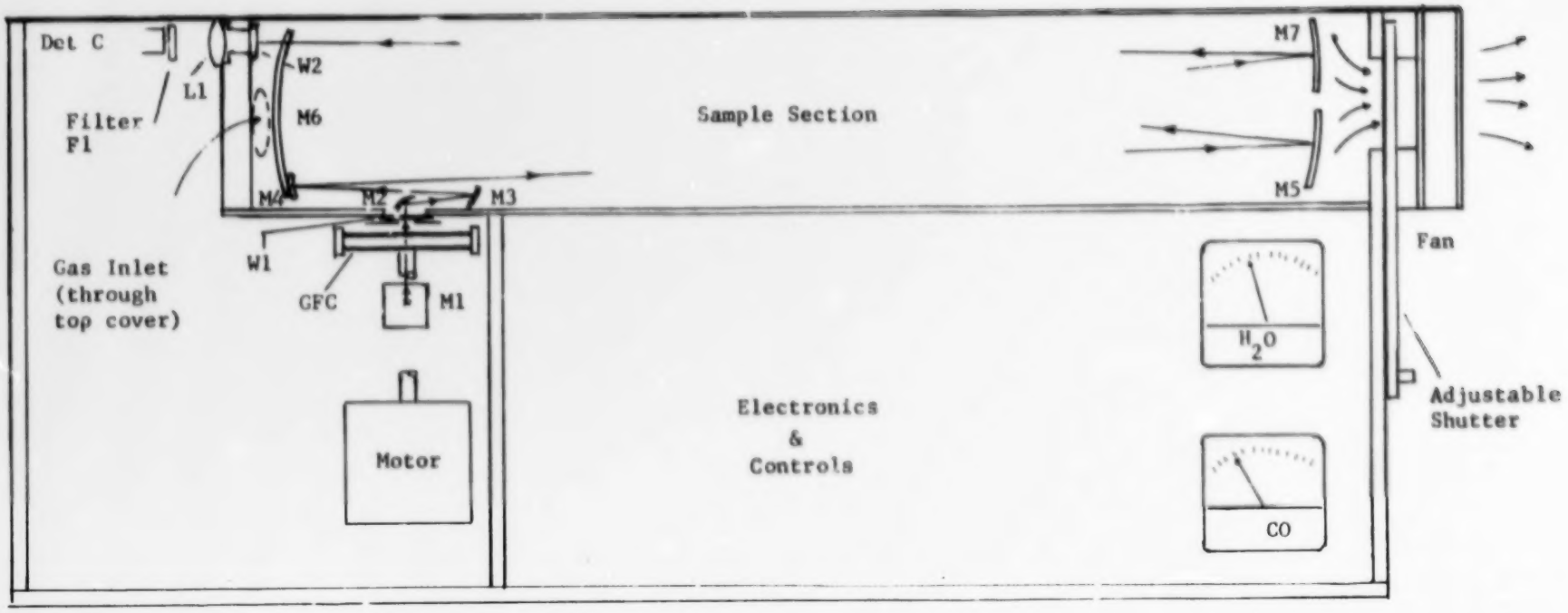

Figure 2 . Optical layout of the components used to measure the concentration of CO. The optical components used exclusively for the H_2O monitor are not included.

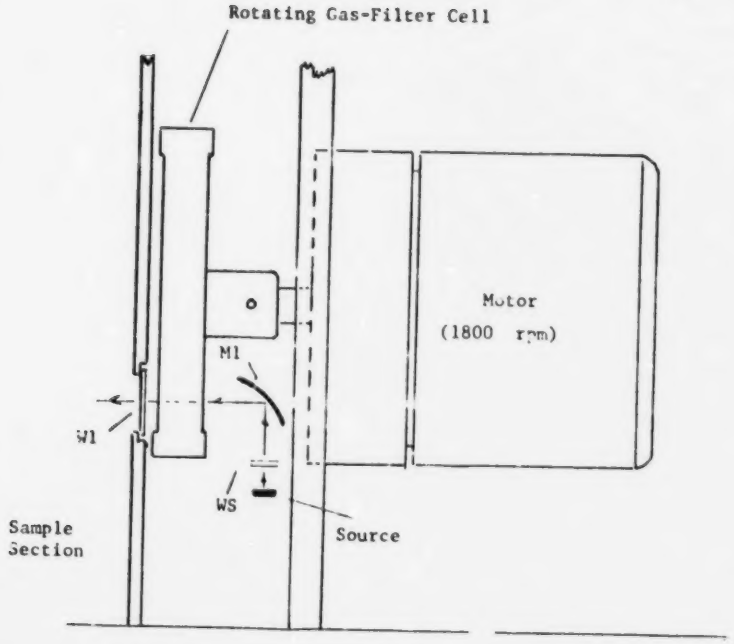

Figure 3. Optical diagram of the entrance optics.

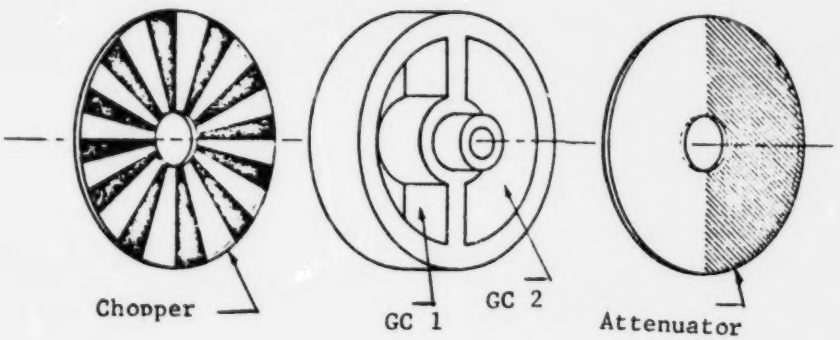

Figure 4. Exploded view of the rotating gas-filter cell.

the same as the average transmittance of the windows with the attenuator in compartment GC2. The cell body is made of stainless steel, and it can be refilled through a small port on the outer end of the cell. The optical path through the CO in compartment GC1 is approximately 5 mm.

A reticle deposited on the surface of the rotating cell window that is located next to window W1 provides high-frequency chopping of the beam. The chopper has 12 opaque strips and 12 openings to produce a high-frequency chopping rate of 360 Hz. When CO is added to the sample section, it absorbs a fraction of the chopped energy that passes through the attenuator side of the rotating cell. However, when the gas-filter side, GC1, of the rotating cell is in the beam, the gas-filter cell absorbs most of the energy at wavelengths where the CO in the sample cell absorbs. Therefore, the addition of CO in the sample section decreases the energy passing through GC2 more than it reduces the energy through GC1. Thus, the 360 Hz chopped signal contains a modulation at 30 Hz, the rotational frequency of the gas-filter cell. The amount of modulation depends on the product of the CO concentration and the path-length in the sample section.

Toroidal mirror M2 placed just inside the entrance window W1 to the sample section directs the incoming beam to mirror M3. The radii of curvature of M2 have been chosen to make mirror M3 nearly conjugate to toroidal mirror M1. Using the toroidal mirror M2 in place of a flat mirror reduces vignetting by reducing the height of the beam of light required on mirror M1 to fill the following optical components.

Spherical mirror M3 directs the incoming beam to mirror M4 where an image is formed of the aperture on the entrance window W1. Spherical mirror M4 directs the energy of the main beam to mirror M5, from where the beam continues through the multiple-pass optical system. Employing mirror M4 with the proper radius of curvature to make mirrors M3 and M5 conjugate to each other avoids vignetting that would occur if a flat mirror replaced mirror M4.

The optical principles of the multiple-pass sample cell are explained in Figure 5 and the legend accompanying the figure. Mirror M6 is approximately 43 cm from mirrors M5 and M7. The mirrors are adjusted to produce 28 passes of the cell before the beam exits through window W2. Therefore, the total pathlength in the sample section is approximately 12 meters.

After the beam exits through window W2, a CaF_2 lens directs the beam through a narrow-bandpass filter and forms an image of mirror M7 on the PbSe element of the detector. A 2-stage thermoelectric cooler maintains the sensitive element of the detector at approximately -25°C in order to improve its detectivity. The filter passes a narrow bandpass that has been selected to provide good sensitivity to CO while minimizing the sensitivity to CO_2 and H_2O, both of which occur in the atmosphere and absorb in the same spectral region.

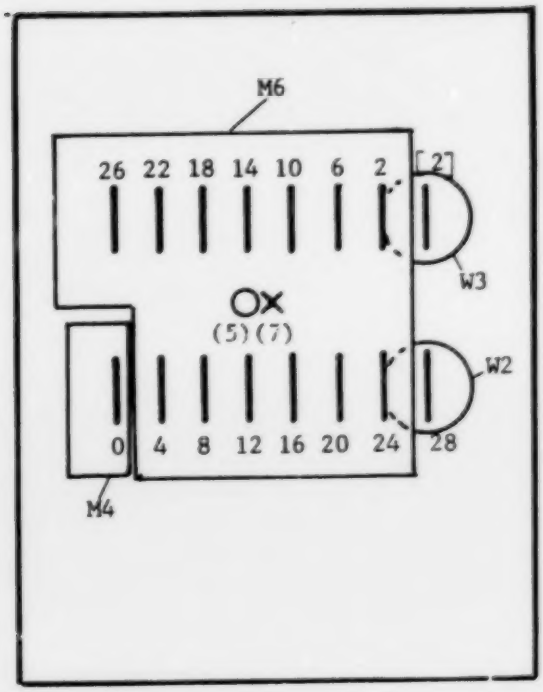

Figure 5. View of the images formed on Mirrors M4 and M6. The view is observed when facing mirror M6 from inside the sample cell. An image of the slit at the entrance window W1 is formed by mirror M3 on mirror M4 at the position indicated by a 0. (See Figure 2 for other components.) Energy directed from M4 to M5 is imaged by M5 on M6 at the position adjacent to the number 2 on M6, which indicates the beam has made 2 passes of the multiple-pass optical system. The energy continued from image #2 to mirror M7, which forms image #4 on mirror M6, etc. Images in the top row are formed by mirror M5; those on the bottom row are formed by M7. After 28 passes, the main beam goes through window W2 to detector C (see Figure 2). Lens L1 forms an image of mirror M7 on the CO detector. The centers of curvature of mirrors M5 and M7 are near the center of the face of the mirror M6 at the positions indicated by corresponding numbers (5) and (7). The number of passes can be changed by re-adjusting the position of the center of curvature of mirror M5.

Energy from the portion of the beam that goes directly from mirror M4 to mirror M7 is imaged after 2 passes near the upper window at the position marked with 2 . This portion of the beam passes on to the assembly of filters, lenses and detectors that measures H_2O concentration (see Figure 6).

Apertures are placed on window W1, mirror M4, and window W2 to reduce stray light and to improve the stability of the instrument. The aperture on window W1 is approximately 1.3 mm wide and 5.5 mm high. This aperture is focussed by mirrors M2 and M3 onto mirror M4. The 3.5 mm wide aperture on mirror M4 is more than wide enough to include the enlarged image of the aperture on window W1. Thus, the aperture on mirror M4 does not restrict any of the main beam; however, it reduces stray energy that might reach the detector by some path other than that of the main part of the beam. The aperture on window W2 limits the height of the beam that can pass through the window but does not restrict the width. At window W2 the beam is higher than it is wide, and the full width can pass through the window and lens L1 to the detector. The masks on the top and bottom of window W2 that form the aperture block rays that might otherwise strike the edge of the lens L1.

H_2O MONITOR

The H_2O monitor makes use of some of the radiant energy that enters the multiple-pass sample cell but does not follow the path described above. The beam reflected from mirror M4 is somewhat oversize so that not all of it is intercepted by mirror M5. Some of the "extra" energy goes directly to mirror M7 which directs it out through window W3 after only two passes of the multiple-pass optical system. The concentration of H_2O is relatively high, and the absorption by the H_2O is sufficiently strong that only two passes of the sample section provide adequate sensitivity to the H_2O. After leaving the sample section through window W3 the beam of radiant energy passes to the assembly of mirrors, filters, and detectors shown in Figure 6. A mask on window W3 serves the same purpose for the energy reaching the H_2O monitor as does the mask on window W2 for the CO channel. The requirements for the stability of the optical beam reaching the H_2O monitor are much less stringent than those for the beam in the CO channel.

When the sample section is filled with argon, or some other non-absorbing gas, the outputs of detectors A and B are made equal by adjusting the relative bias voltage across the two detectors. When H_2O is added to the sample section, the amount of radiant energy chopped at 360 Hz that reaches detector A is diminished because of the H_2O absorption in the spectral region passed by filter A. The presence of the H_2O in the sample section makes only a very small, if any, difference in the amount of chopped energy incident on detector B. A tuned amplifier and synchronous demodulator measures the difference between the two signals from the two detectors. This difference can be related to the concentration of H_2O in the sample section.

The output V_B from detector B is used as a reference signal for the synchronous demodulator that measures $(V_B - V_A)$. An AGC circuit maintains the amplified signal from detector B at a constant level to account for the changes in source brightness, detector temperatures, and other factors that may affect the detector output. The gain of the first stage of the amplification of the

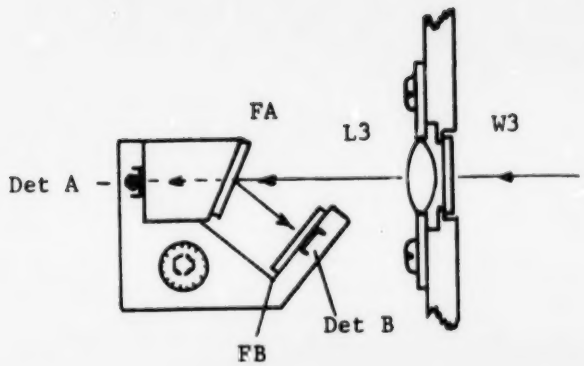

Figure 6. Optical diagram of the H_2O monitor. After making two passes through the sample cell, the beam exits through window W3 and lens L3. Filter FA transmits a narrow spectral interval containing strong H_2O absorption to detector A. The wavelengths of energy reflected by Filter FA are directed to filter FB, which transmits to detector B a narrow interval that is adjacent to the interval passed by filter FA and contains little or no H_2O absorption. The H_2O concentration is measured by comparing the amounts of chopped energy (at 360 Hz) on the two detectors.

signal from detector A is also automatically decreased, or increased, by the AGC by the same factor as the change in the gain of the signal from detector B. The output of the synchronous demodulator is thus automatically made proportional to the quantity $(V_B - V_A)/V_B$. This quantity can be related directly to the H_2O concentration and is essentially independent of detector temperature, source brightness, or dirt on windows or mirrors.

The output of the H_2O monitor is fed directly to the main electronics used to measure the CO concentration. A "correction factor" adjustment can be made so that the signal fed to the CO electronics from the H_2O monitor exactly accounts for the interference by H_2O in the CO channel. The correction factor is adjusted by introducing into the sample a CO-free sample with the H_2O concentration approximately equal to that expected in samples to be measured. The presence of the H_2O in the sample section produces a small signal in the output of the CO channel because of the interference of the H_2O. The correction factor is adjusted to nullify the signal from the CO channel. Since the interference in the CO channel by H_2O and the output of the H_2O monitor are both essentially directly proportional to the H_2O concentration, the H_2O interference is properly accounted for over a wide range of H_2O concentrations. It should be noted that the H_2O monitor does not need to be calibrated accurately in order to achieve the proper correction. If an accurate measurement of the H_2O concentration is desired, the H_2O monitor can be calibrated. The precision is approximately 0.01% of H_2O, and the accuracy would probably be limited by the accuracy of the standard gas used for the calibration.

SECTION VI

SAMPLING AND CALIBRATION

GAS HANDLING

The air to be monitored can be circulated through the sampling section by either of two different methods. In the first method, both the top and side covers for the sample section are removed so that the ambient air is free to circulate through the monitoring beam. This method has the advantages that no fans or pumps are required; however, it has the disadvantage that the covers for the sample section must be re-installed in order to flush the sample section with a non-absorbing gas to adjust to zero.

The second method of sampling is usually more satisfactory and takes place with the covers on the sample section. The air being measured enters the sample section through a hole in the small top plate at the end near mirror M6. It then traverses the sample section lengthwise and exits through holes in the end plate behind mirrors M5 and M7. A small exhaust fan mounted on the end behind mirrors M5 and M7 draws the air through the sample section at a steady rate. The flow rate can be adjusted by either varying the fan speed or by varying the size of the opening where the air emerges from the sample cell. An adjustable shutter on the end of the instrument is used to adjust the size of the opening. The opening is completely blocked when the shutter is pushed farthest in. The opening and the shutter are shaped so that the size of the opening can be controlled with good precision when it is first being opened. When the shutter is moved more than approximately 0.4" from the closed position, the size of the opening increases more rapidly as the shutter is moved toward the wide-open position. If it is desirable to leave the cell completely closed with no circulation for an extended period of time, it is advisable to turn off the exhaust fan to decrease leaks around the shutter. A bolt with a knurled head is threaded through the supporting block for the sample exhaust fan. When this bolt is tightened it is forced against the shutter to form a tighter seal.

All of the holes in the wall of the sample section through which screws extend have been potted with RTV to prevent leakage. It is unlikely that any adjustments of the multiple-pass optics will be needed. If a minor adjustment is required, the RTV can be removed from the screws that will be moved. Windows W1, W2 and W3 are also bonded in place with RTV. The gasket material on the covers for the top and backside of the sample section provides adequate seal for most applications. However, if a gas circulation system is used that would cause the pressure in the sample section to drop significantly below atmospheric pressure, it would be advisable to provide a better seal around the edges of the cover plates.

The exhaust fan is designed for relatively high flow rates with little pressure drop in the airstream. Because the air enters the sample section very near the monitoring beam, the rise-time of the instrument can be made very short. For example, a small amount of gas entering the sample section near M6 can cause an observable change in the instrument output within 1 or 2 seconds, depending upon the rate of flow. In some applications, it is desirable to place the instrument inside of a building or possibly in an enclosed vehicle, and to draw air in through a probe from the outside. In this case, the time lag will depend on the flow rate and upon the volume of the line in the probe. In this type of application, it is also advisable to not draw the air in through the sample section by the exhaust fan located on the exit end of the sample section. A small pump or fan should be located in the intake line just ahead of the sample section. The exhaust fan at the exit end of the sample section would be turned off or removed, and the shutter on the exhaust end would be left slightly open to allow the air to exit while maintaining the pressure in the sample section very near, or slightly above, the ambient atmospheric pressure. This type of circulating system would decrease the amount of air from within the enclosed building or vehicle that might leak into the sample section.

The zero-reading of the instrument is adjusted electronically when the sample section is being flushed with argon, or some other non-absorbing gas. Nitrogen should ordinarily not be used for this purpose because commercially available nitrogen usually contains a few tenths of a ppm of CO. This amount of CO naturally interferes with the zero setting. The gas line is connected to the gas inlet near mirror M6, and the shutter on the gas outlet should be opened between approximately 0.2" and 0.5". The sample exhaust fan should be turned off. By observing the signal output, it is possible to determine when the sample section has been completely flushed. Standard samples of known CO concentration are flushed through the sample section in the same manner in order to check the span calibration.

When checking the span calibration for the H_2O monitor, or when adjusting the H_2O correction factor, the non-absorbing gas can be bubbled through liquid water at about room temperature. With a flow rate between 1 and 3 liters/minute for about 5-10 minutes, the H_2O concentration in the cell will probably increase to within 10% of the concentration corresponding to saturation at the temperature of the liquid water. Some time is required for the initially rapid rate of adsorption on the walls to decrease. Less time is usually required to flush the H_2O mixture from the sample cell with dry argon.

CALIBRATION CURVES

Figure 7 shows the calibration curves for the four ranges A, B, C, and D for the instrument at the time it was delivered to EPA. Each of the four individual span calibration potentiometers on the top panel changes the full-scale concentration for the corresponding channel. The master span calibration potentiometer on the top panel changes the gain for each of the four ranges by the same factor.

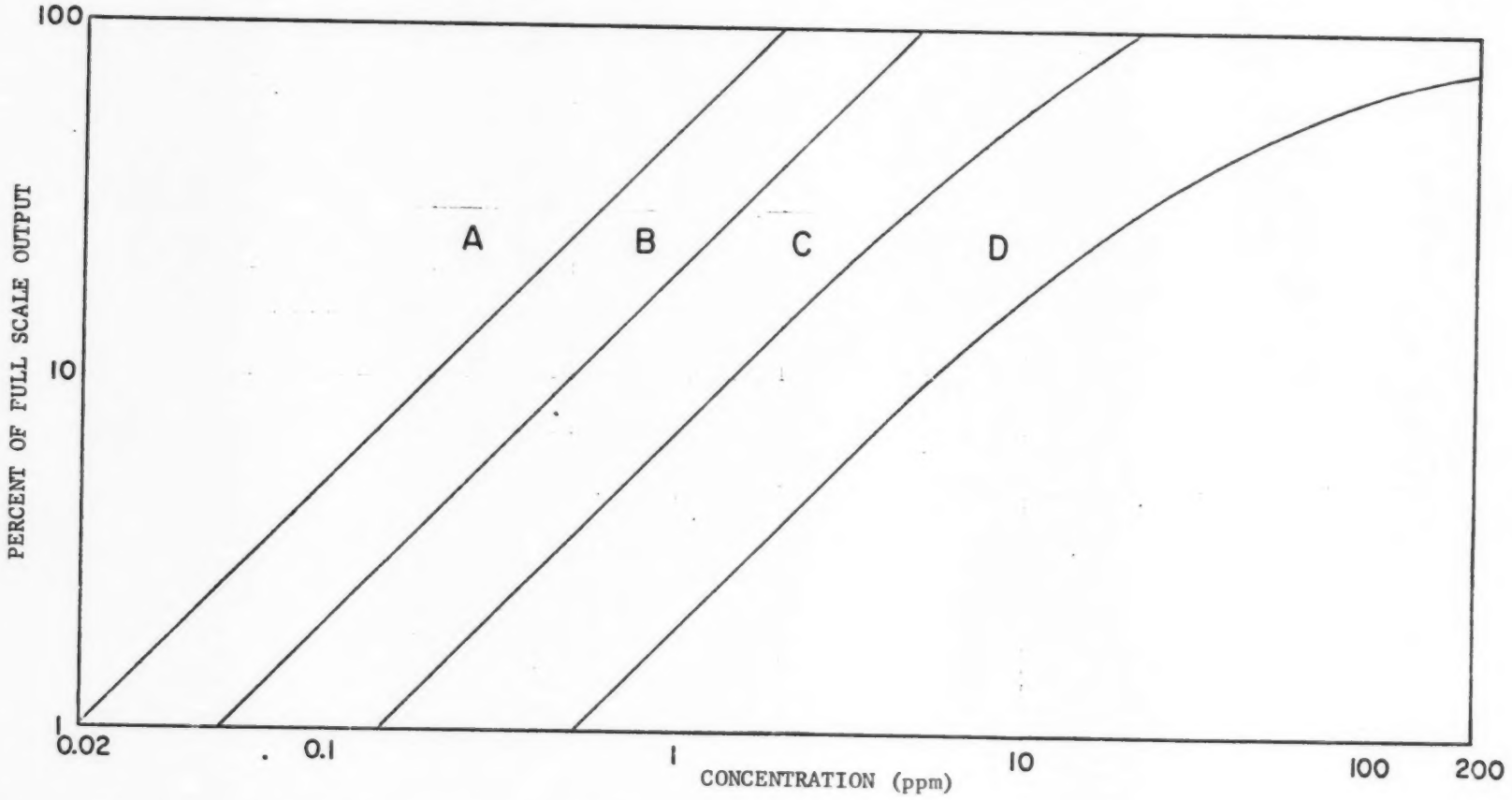

Figure 7. Calibration curves relating the output signal to the concentration of CO.

SECTION VII

ELECTRICAL CIRCUITS AND CONTROLS

Wiring diagrams of the electrical power circuits are shown in Figures 8, 9 and 10. All of the circuits contained in the main instrument box are illustrated in Figure 8. The male pin connector is mounted on the front panel of the main instrument box. The motor transformer supplies 60 V ac power for the motor that drives the rotating gas filter cell when operating in both the ac mode and the dc mode. The 5 V dc power supply, the $\pm$ 15 V dc supply, and the source transformer are all used in the ac mode only. Power for the sample exhaust fan is supplied to the fan motor through a plug on the end of the instrument near the fan. The cooling fan is powered through a terminal strip located near the fan. Both the exhaust fan and the cooling fan are interchanged when converting from ac to dc, or vice-versa. The ac power switch on the front panel is in the active circuit only during ac operation.

The power cables for both ac and dc operation are illustrated in Figure 9. The appropriate cable plugs into the male pin connector on the front panel of the main instrument box. For ac operation, the end of the power cable opposite the main instrument plugs directly into a 115 V ac power line. The corresponding end of the dc power cable plugs into the front of the power supply assembly.

The power supply assembly and the battery cable that connects it to the battery pack are illustrated in Figure 10. These components are used only during dc operation. Power for the 60 Hz synchronous motor that rotates the gas-filter cell is supplied by the dc-to-ac convertor. The 24 V dc-to-$\pm$ 15 V dc converter supplies power for the electronics during dc operation. During cool weather, the cooling fan in the power supply assembly may not be required. No tests have been performed with the cooling fan disconnected.

A commercial battery charger can be connected to the batteries through a 3-pin plug mounted on the front of the power supply assembly. In order to charge the batteries, the rotary switch on the front panel of the power supply assembly must be in the charge position. A small plate bolted on the front of the battery charger prevents the charger from being switched to the 12 V position. For normal dc operation, the rotary switch must be in the run position, and the 24 V dc and 6 V dc switches must be turned on.

The wires on the battery cable are bundled in pairs. One wire in each bundle has a red band near the end to indicate that it connects to the positive battery terminal. The other wire of the same pair has a black band and connects

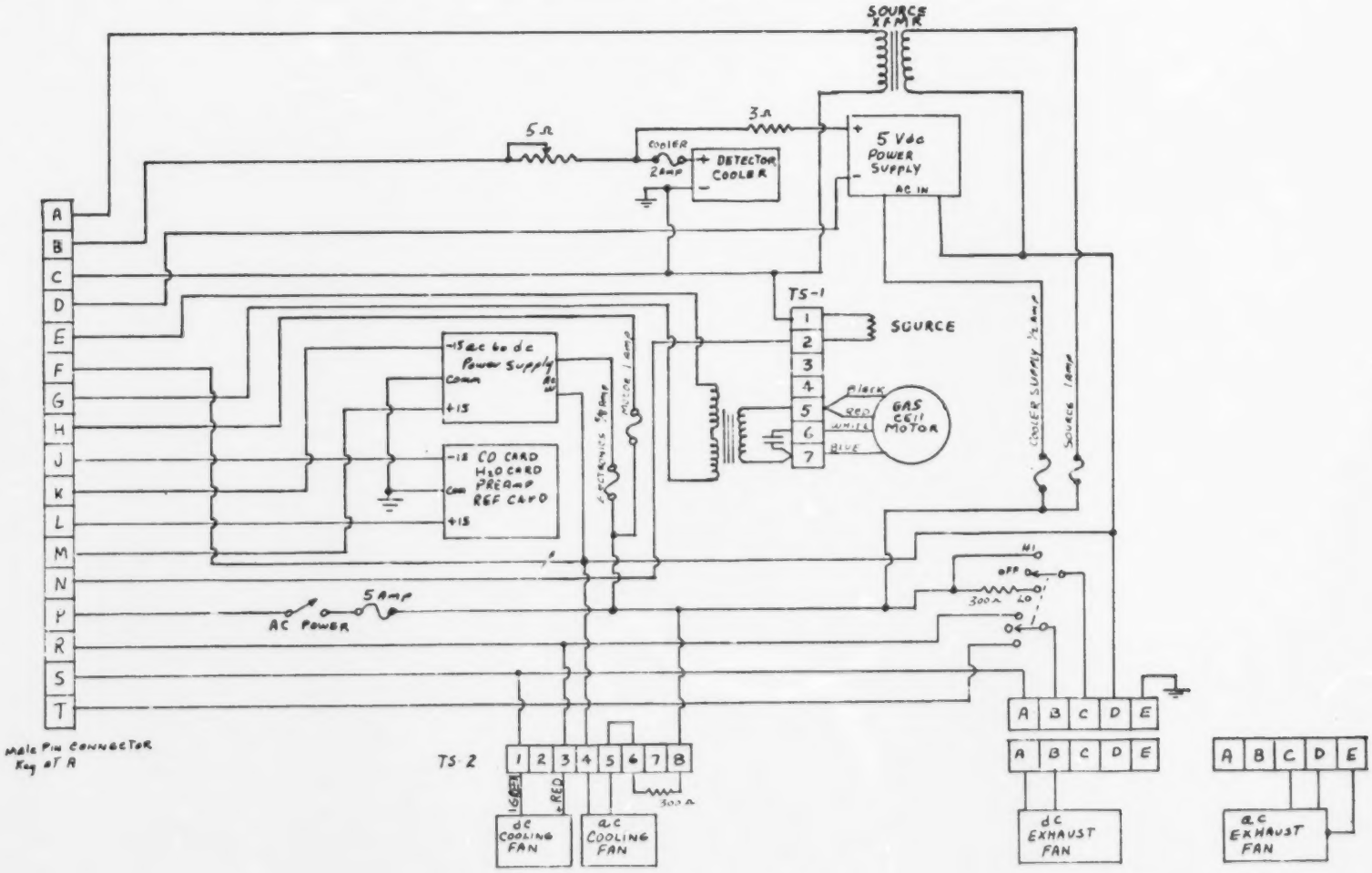

Figure 8. Electrical wiring diagram of main instrument box.

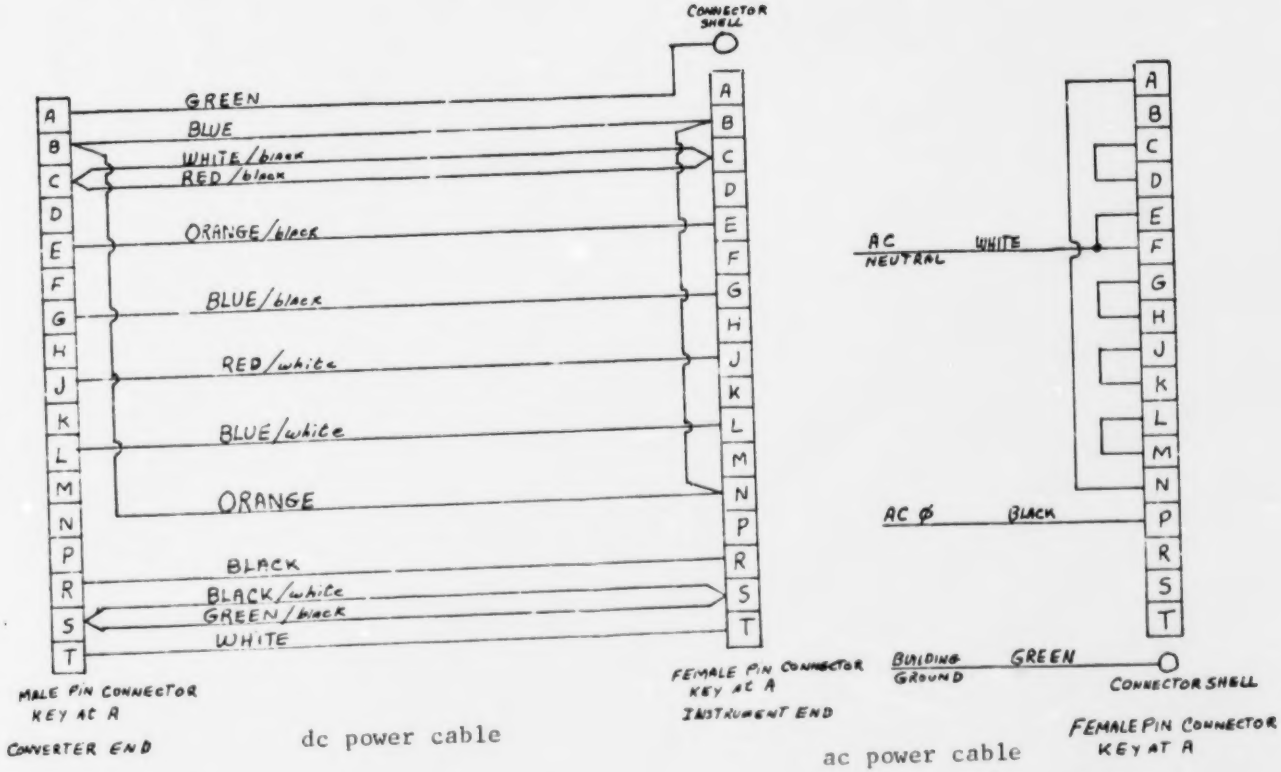

Figure 9. Wiring diagrams for dc and ac power cables.

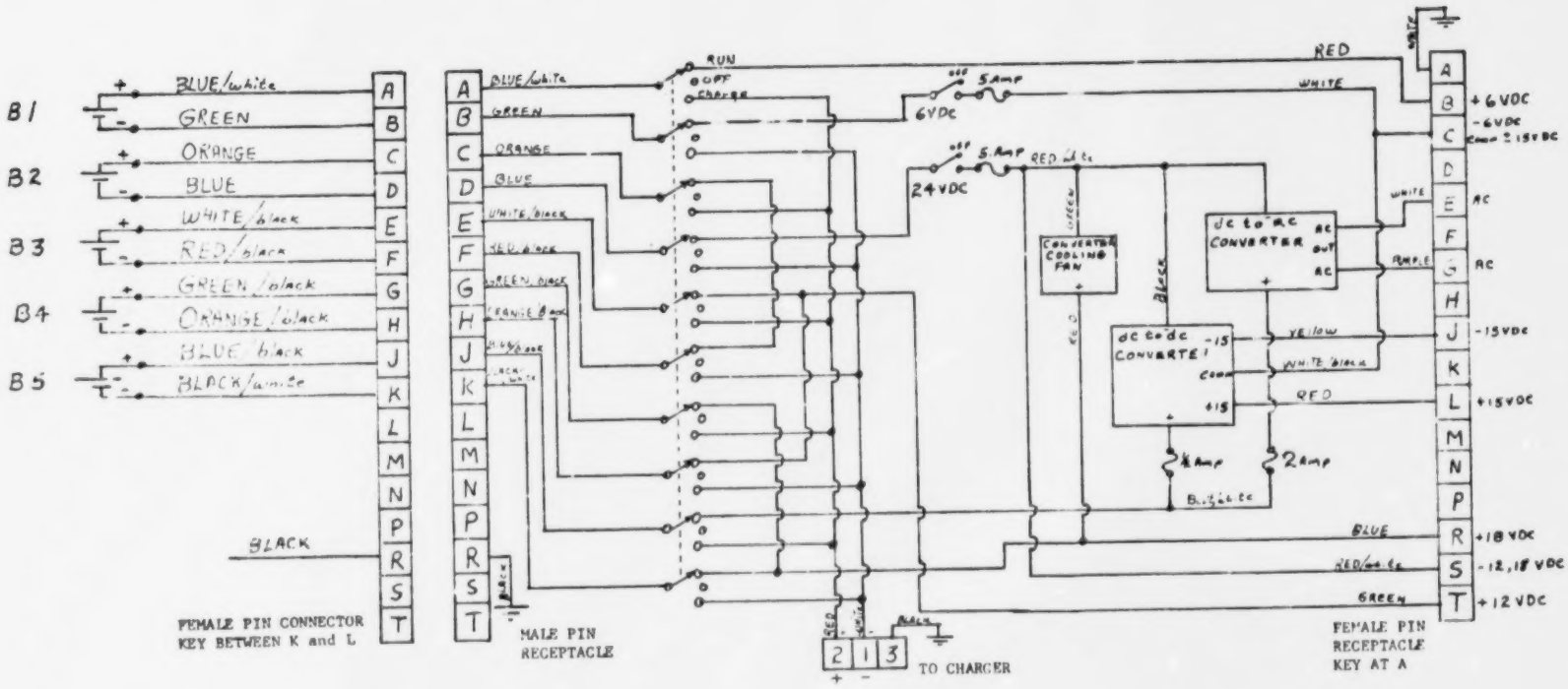

Figure 10. Wiring diagram of the battery cable and the power convertor assembly.

to the negative terminal of the same battery. Battery No. 1 powers the detector cooler and the radiant energy source. By using two batteries connected in parallel in the place of battery No. 1, the maximum operating time from fully charged batteries can be increased from approximately 4 hours to 8 hours. Batteries 2, 3, 4 and 5 provide power for the other components for approximately 8 hours. The total power consumed during dc operation is approximately 42 watts.

Most of the electronic circuitry is contained on the four circuit cards indicated in the lower panel of Figure 1. The small preamplifier card is located near the detector and the bias battery, and the larger, main electronics card is mounted on the underneath side of the top panel. All of the controls on the main card are easily accessible when the top cover is inverted as shown in the lower panel of Figure 1. All of the electronic components used to process the signals from the two detectors in the H_2O channel are contained on the H_2O electronics card, which is mounted to the baseplate beneath the main electronics card. The reference card processes the signal from the reference pick-up and supplies a 30 Hz reference signal for the synchronous demodulator in the main electronics.

The primary purpose of the main electronic circuits is to process the signal from the detector in the CO channel and to produce a dc output signal that is proportional to V_a/V_c, the ratio of the detector signal components at the corresponding frequencies f_a (30 Hz) anf f_c (360 Hz). The 30 Hz component is processed by a synchronous demodulator as a modulation of the 360 Hz carrier signal. An automatic gain control circuit maintains V_c, the amplified component of the carrier signal at a constant level. The instrument output is proportional to V_a, the amplified signal resulting from the 30 Hz modulation. Because V_c is constant, this output is therefore proportional to the ratio V_a/V_c, which is directly related to the concentration of CO in the sample cell.

The output signal can be read from the meter on the top panel or from an output jack designed for use with a strip-chart recorder. A switch and potentiometer mounted near the output jack make it possible to vary the signal at the output jack corresponding to full-scale of the panel meter from approximately 0.01 volts to 10 volts. The electronic time constant can be switched to either 0.3, 1, 3 or 10 seconds.

The span calibration is checked or adjusted with standard samples of CO in argon or CO in clean air according to the following: Four different ranges of sensitivity are available; range A is the most sensitive and is used for the lowest CO concentrations; and range D is the least sensitive. The range switch indicates the range being used. At the time the instrument was delivered to EPA, full scale meter deflection (FS) corresponded approximately to the following CO concentrations: Range A, 2 ppm; B, 5 ppm; C, 20 ppm. Because of excessive non-linearity between the signal output and the CO concentration for higher concentrations, it was not

practical to adjust range D to match a fixed concentration. Instead, half-scale was adjusted to correspond to 50 ppm. Within certain restrictions, the span potentiometers for each range can be re-adjusted for other sensitivities. Calibration curves for the instrument at the time it was delivered to EPA are shown in Figure 7

The electronics for the H_2O monitor produce a dc signal proportional to $(V_B - V_A)/V_B$, where the voltages V_B and V_A correspond to the amplified signals from detectors B and A, respectively (see Figure 6). This voltage ratio is proportional to the H_2O concentration. An automatic gain control circuit maintains V_B at a constant level and produces the same fractional change in the amplification of the signals from both detectors. Thus, the ratio $(V_B - V_A)/V_B$ is proportional to the difference between the two amplified detector signals and is, to a good approximation, independent of source brightness, dirt on windows, etc.

The output of the H_2O monitor is displayed on a panel meter and on an output jack similar to the ones in the main CO channel. By adjusting the H_2O span potentiometer, full-scale reading of the H_2O panel meter can be varied from less than 1% H_2O to more than 10% H_2O. Another potentiometer associated with the H_2O monitor is used to vary the "correction factor", which is the fraction of output of the H_2O monitor that is fed into the CO channel. This correction signal is adjusted to automatically account for a small amount of interference by H_2O in the CO channel. By carefully making this adjustment, any remaining error in the CO channel due to the interference by atmospheric H_2O can be made less than 0.01 ppm of CO.